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AN EXPERIMENT ON THE INITIAL CONDITIONS FOR A MESOSCALE FORECAST

by

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ABSTRACT

A 6 hour forecast starting at midday on a good sea breeze day has been repeated for seven different sets of initial conditions. The initial values for each field could either be given by an 8 hour mesoscale forecast valid at 1200 GMT or interpolated from a synoptic scale forecast valid at the same time. It was found that changing the initial temperature field had an important effect on the subsequent forecast, but the impact of changing the initial wind field was relatively small. Changing the initial surface pressures had no visible effect on any aspect of the subsequent forecast other than the forecast of surface pressure itself.

INTRODUCTION

In recent years there has been an increase in the use of high resolution numerical models to forecast atmospheric motion on regional and local scales (30 km to 300 km). (Anthes & Warner (1978), Fritsch & Chappell (1978), Perkey (1976), Pielke (1974)). The design and testing of a numerical model is usually the first step taken in developing the ability to produce numerical weather forecasts, but, in practice, the integration of the model equations is only one component in a complex system. In particular, numerical forecasts require initial values for the model variables, and the quality of the inital conditions often contributes at least as much to the accuracy of the forecast as the model itself.

On large horizontal scales ($>$ 1000 km) the real atmospheric wind and mass fields are in approximate geostrophic balance and, during the early stages of model forecasts, the wind field adjusts to the mass field. Thus, for forecasts on a large scale, it is vital that the initial mass field is analysed as accurately as possible. The information content of wind observations is only preserved if they are used in determining the initial mass field. For atmospheric systems on an intermediate scale ($\sim$ 1000 km), and in the tropics, the situation is reversed and it is important to obtain the best possible initial wind field. We do not know which meteorological fields control developments on local weather scales ie $\sim$ 100 km and less.

Carpenter (1979) has described a case study in which a model developed by Tapp and White (1976) was used to forecast well developed sea breezes over England and Wales. This forecast was for the 24 hours from 0400 GMT, and was made using the same model and grid as in the present work. During the first eight hours, sea breeze fronts developed along much of the coastline and, by 1200 GMT, they were well established and beginning to penetrate inland. The experiment described in this paper uses this earlier forecast as a control, or "truth", in an experiment on the initial conditions for a six hour forecast from 1200 GMT to 1800 GMT. The new forecast was repeated with seven sets of initial conditions that

that were derived in part from the original mesoscale forecast and in part from a synoptic scale forecast valid at 1200 GMT. Changing from the mesoscale model data on a grid of 10 km to synoptic data on a grid of 100 km might be regarded as simulating the effect of using an inadequate network of observations. A series of experiments of this sort should indicate which meteorological parameters must be specified, and ought to be observed, in detail in order to provide accurate short range forecasts.

The effects of water phase changes and latent heat release are not important in the sea breeze situation studied here, and they have not been included in the forecast model. However, it is likely that they are more central in other mesoscale situations, and this should be investigated in future experiments. Kreitzberg and Rasmussen (1977) and Atkins (1974) have considered the impact of varying the initial humidity field on the regional scale ($\sim$ 1000 km).

The remainder of this paper is in four sections. The experiment itself is described in Section 2, and the results are presented in Section 3. The extent to which these results can be generalised is discussed in Section 4.

2 THE EXPERIMENT

The object of the experiment was to determine the effect on a small scale model forecast of replacing detailed and accurate information in the initial conditions by smooth (ie less detailed) information obtained from a large scale model. In particular, we wished to know the relative impact of varying different model fields. The situation chosen for the study was a good sea breeze day over the UK, 14 June 1973, which was initially described by Simpson, Mansfield and Milford (1977). Carpenter (1979) has described an experimental forecast for this day, and this forecast provided the raw material for the experiment.

The original forecast was for the 24 hour period from 0400 GMT on 14 June 1973. The initial conditions for this forecast were obtained by interpolating a

synoptic scale model forecast on a grid with a resolution of 100 km onto the 10 km mesoscale model grid. Because of the method of interpolation and the difference in the grid resolutions, the resulting initial conditions were very smooth, but, in view of the time of day to which the initial conditions refer and the nature of the subsequent forecast, this probably had little effect on the forecast after about 0800 GMT. The same method was used to obtain "final" conditions, which were needed to provide lateral and upper boundary tendencies for the mesoscale model forecast.

The forecasts reported in this paper were for the 6 hour period from 1200 GMT to 1800 GMT, and the original mesoscale model forecast, from 0400 GMT, was used as a control. The initial values of the forecast variables were obtained either from the control forecast, or from an interpolation (like that for the initialisation described above) of a large scale model forecast for 1200 GMT. Seven sets of initial conditions were generated by making the choice for the various model fields in different combinations. The computer code used for the forecast was the same in each case, as were the initial soil surface temperature, and the solar warming.

Although the basic model equations are non-hydrostatic, the hydrostatic relation is very closely satisfied by the forecasts so the temperature and pressure are not truly independent variables. [The model should maintain hydrostatic balance in the same way as the atmosphere]. Thus the mass field is determined by the temperature at each level and a single reference pressure, which was taken to be the surface pressure. Similarly, since the atmosphere is nearly incompressible, the vertical velocity is effectively determined by the horizontal velocities through the continuity relation, and no attempt was made to vary the vertical velocity independently of the horizontal velocities. The horizontal velocities or the temperature could have been varied independently for any number of levels but in practice the wind and temperature were varied as a whole, with the exception described below. Thus either the mesoscale model forecast or the large scale model forecast were used to provide initial values for each of:-

(i) the winds,

(ii) the temperatures

(iii) the surface pressure.

When the surface pressure and all the temperatures were taken from the mesoscale model, the pressures at other levels were also taken from the mesoscale model; otherwise, the hydrostatic relation was used to calculate the pressures. In addition to these, variations were made to determine the effect of having no temperature observations other than those at low levels. The mesoscale model forecast was used for the temperature at the lowest model level and the temperature at other levels was taken from the large scale model forecasts. Where this prescription implied lapse rate instability, this was removed and a well mixed layer of uniform potential temperature (calculated from the mesoscale forecast at the lowest level) was used.

The initial conditions from the seven forecasts are summarised in Table 1. The nature of the differences between the three choices that were made for the temperature is illustrated by Figure 1, which is a NS cross section passing just east of the Pennines and through the Midlands. The two choices that were made for the wind are illustrated by Figure 2 (which is the same section), and the two choices for the surface pressure are shown in Figure 3.

3 THE RESULTS

The quality of any single forecast is of little interest in the present context; the purpose of the experiment is to compare the forecasts in order to come to some conclusion about the relative importance of the various fields in the specification of the initial conditions.

An examination of Table 1 shows that there are three comparisons showing the effect of removing detailed wind information, two comparisons for both of the changes made in the initial temperature fields and only one comparison showing the effect of removing the detailed surface pressure information. In each case, the effect of making a change was independent of the initial conditions in which the change was made. Thus, for example, the effect of removing the detailed mesoscale temperature information can be found by comparing MM with MS or by comparing SM with SS, and no ambiguity has been found. Even though the forecasts depend on the initial wind field used, the

changes due to varying the temperatures do not.

(i) The effect of changing the initial wind fields

The three tests of the effect of changing the initial wind fields all indicated that the effect was small ie well within the range of errors due to other (eg numerical) effects. Figure 4 shows the 2 hour low level wind forecasts for SM (Figure 4(a)) and MM (Figure 4(b)), Figure 5 shows these winds at 6 hours and Figure 6 shows the 2 hour forecasts of vertical velocity. Comparing forecast SM with the control forecast MM shows the effect of removing detailed and accurate information about the winds in the initial conditions. Eight areas or features in which it was reasonable to expect to see changes in the more detailed pictures not shown here were identified:-

A. The general flow or the shear line north and east of the Isle of Man.

B. The shear line in N Wales.

C. The shear line in S Wales.

D. The general flow or the shear line in the South West Peninsula.

E. The wind direction along or north of the south coast.

F. The inland penetration of the south coast sea breeze.

G. The sea breezes in East Anglia.

H. The north east coast shear line.

The results of these comparisons, and the others reported below, are summarised in Table 2. It will be seen that the small effect of changing the initial winds can be explained, at least qualitatively, as a movement of the shear lines in the direction of the synoptic wind.

(ii) The effect of changing the initial temperature field

The effect of replacing detailed and accurate temperature fields with smoother fields obtained by interpolating synoptic scale data can be seen by comparing forecasts MM and MS (or, with the same result, forecasts SM and SS). These two forecasts are shown in Figures 4(b) and 4(c), 5(b) and 5(c) and 6(b) and 6(c). It can be seen that this change in the initial temperature fields leads to substantial

differences in the subsequent forecasts. Some of these differences are shown in Table 2, but the forecasts are so dissimilar at 2 hours that there is no value in comparing their treatment at that time of the eight features listed above.

As described in the previous section, the initial temperature fields were varied in two ways. The change shown as (ii)(a) in Table 2 was to replace the control mesoscale model forecast temperature for 1200 GMT with those from the synoptic scale model forecast at all levels except the lowest, and then remove the convective instability. This gives initial temperatures that are qualitatively very similar to the mesoscale model forecast (see Figure 1) and it had a small effect ie well within the range of errors due to other (eg numerical) effects.

On closer examination, particularly using the larger number of charts not shown here, it is clear that all the forecasts are progressing through the same stages. Only forecasts SS and MS in which the information about the developments of a surface mixed layer due to convective heating and the inland penetration of cold air is not represented in the initial data, show any substantial deviation, and they appear to run about three hours behind the other forecasts. Given that the initial wind fields have little effect on the subsequent forecast, this can be explained by observing that forecasts SS and MS must establish a temperature contrast between the land and sea air before any further development can take place, while in all other cases the temperature contrast exists in the initial conditions.

(iii) The effect of changing the initial surface pressure

Of all the comparisons this was the most dramatic. Throughout the 6 hour period the two forecasts that showed the effect of this change were so alike that they could not be distinguished using graphical output, such as that shown here, except by looking at the forecast surface pressure itself. It is concluded that the details of the initial surface pressure field have no dynamical effect on the subsequent forecast for this sea breeze day.

4 DISCUSSION

It would be desirable to appeal to some general theory that explained the results of these experiments, but that does not appear to be possible. Geostrophic adjustment theory (eg Temperton (1973)) is usually said to show that the mass field adjusts to the wind field for small horizontal scales, so the results are superficially surprising. However that theory is only appropriate when the phenomena of interest are geostrophic (and thus have small horizontal divergence) and when the basic linearisation assumptions are reasonable. Neither of these requirements is satisfied in the present study. In particular, it is difficult to use a general approach based on a linearisation to describe a situation in which a region of vanishing static stability is embedded in an environment with a reasonably large (2×10^{-2} sec^{-1}) static stability. Nevertheless, the usual normal mode analysis does explain the results concerning the change in surface pressure, which will be discussed in the last paragraph of this section. The results from geostrophic adjustment theory that are needed in the last paragraph are derived in the Appendix.

In order to understand the results we must concentrate on the dominant aspect of all the forecasts, the development of sea breezes. Simpson, Mansfield and Milford (1977) have explained sea breezes as gravity currents in which the release of potential energy is balanced by an increase in the kinetic energy of the land air as it passes over the head of the sea breeze front, and by dissipative effects. It seems obvious that the existence of a temperature contrast necessarily implies motion, in this case a sea breeze, and that motion that has developed in response to the existence of a temperature contrast must decay of the temperature contrast is removed. Of the seven forecasts, only MM and SS had initial conditions that are balanced. The entire initial conditions for MM were taken from the control mesoscale model forecast and the sea breezes are well developed. The initial conditions for SS were all obtained by interpolating the large scale model forecast and there is no land/sea temperature contrast and no sea breeze motion. In the first two remaining paragraphs of this section the adjustment of

the other initial conditions, so that each forecast effectively follows either MM or SS, is discussed.

(i) The adjustment of unbalanced winds to an existing temperature contrast

The initial conditions for forecast SM are shown, in cross section, in figures 1(b) and 2(a). The warm well mixed layer over land and the relatively cold stable air over the sea imply a temperature contrast near the coast that has produced the sea breeze vortex shown in figure 2(b) and must be inconsistent with the initial winds used. In order to find the time scale for the inland acceleration of the dense sea air, consider the equation for the component of vorticity

$\xi = \frac{\partial w}{\partial y} - \frac{\partial v}{\partial z}$ normal to the sections shown

$$\frac{\partial \xi}{\partial t} = c_p \left(\frac{\partial \theta}{\partial z} \frac{\partial P}{\partial y} - \frac{\partial \theta}{\partial y} \frac{\partial P}{\partial z} \right) \qquad 4.1$$

where non linear and dissipative terms have been omitted. θ is the potential temperature, and P is the Exner function $(p/p_r)^{R/c_p}$, which can be calculated from θ using the hydrostatic relation $c_p \theta \partial P/\partial z = -g$. In the present context, the first term on the right of equation 4.1 can be neglected, and

$$\frac{\partial \xi}{\partial t} = \frac{g}{\theta} \frac{\partial \theta}{\partial y} \qquad 4.2$$

When this expression is averaged over a box circumscribed by the sea breeze vortex in Figure 2(b) and containing the sea breeze front, we find $\partial \xi/\partial t \approx$ $1.5 \times 10^{-6} \text{sec}^{-2}$. (Note that although this box is about 1 km deep, the sharp temperature gradient is confined to the bottom two levels, ie a layer about 150 m deep). Averaged over the same box, the vorticity $\xi \approx -\partial v/\partial z$ of the sea breeze vortex is $\approx$ $5/1000 = 5 \times 10^{-3} \text{sec}^{-1}$. This indicates that the time scale over which the sea air will accelerate and the adjustment take place is $\xi / (\partial \xi/\partial t) \approx$ 55 mins. In the integrations the process is almost complete in an hour, in good agreement with this naive analysis.

These arguments and results suggest that the gravity current balance described by Simpson et al is achieved quickly, ie more rapidly than the

production and enhancement of the land/sea temperature contrast by solar warming of the land.

(ii) The response of the wind field when the temperature contrast is removed

The initial conditions for forecast MS include the sea breeze vortex (Figure 2(a)) imposed on a uniformly stable atmosphere (Figure 1(b)). The restoring effect of the stability means that the vortex will be dispersed as gravity waves. The gravity wave energy will move with the group velocity away from the sea breeze front, and will then either be damped by the diffusion in the model or become indistinguishable from the "noise" that is always present in real data atmospheric model forecasts.

The dominant horizontal and vertical wave numbers, k and m of the gravity waves are given by the horizontal and vertical scales of the vortex. Thus $k \approx \pi/(3 \times 10^4) \approx 10^{-4} m^{-1}$ and $m \approx \pi/(1400) \approx 2.25 \times 10^{-3} m^{-1}$. The Brunt-Vaisala frequency N is about $1.5 \times 10^{-2} sec^{-1}$, so the horizontal group velocity $\pm N/m$ is $\pm 7 ms^{-1}$, and the vertical group velocity Nk/m^2 is $\approx 0.3\ ms^{-1}$. Hence the gravity wave will propagate up out of the lower layers in which the sea breeze develops, ie through a depth of, say, 1800 m, in 100 mins, and in that time the effect of the vortex will be spread, horizontally, over slightly more than three times the width of the original vortex.

Forecast MS has been examined at 20 min intervals and its behaviour bears out this discussion. Once again the adjustment of the wind field to the mass field is relatively rapid, ie more rapid than the boundary layer processes that are responsible for the development of sea breezes.

(iii) The effect of changing the initial surface pressure

Two forecasts started with initial conditions which differ only in the surface pressure. In both cases the hydrostatic relation was satisfied, so the pressure change was uniform with height and spread well beyond the sea breeze, which affects only the lower part of the atmosphere. Thus the earlier objections to the use of geostrophic adjustment theory do not apply

in this case, and we can use the results derived in the Appendix for the vertically constant $m = 0$ modes. This theory states that a vertically uniform pressure perturbation, on these horizontal scales, will manifest itself as sound waves (Lamb waves) only. As sound waves it will have a small effect on the winds and no effect on the potential temperature and this explains the lack of any visible difference between these forecasts.

The sound waves propagate rapidly, but are reflected at the boundaries so the only mechanisms that will remove them are the time filter and the lateral diffusion of momentum. The time filter (Asselin (1972), with a coefficient of 0.02) is quite weak. The highest frequency sound waves have a period of $4\ \delta t$ (because of the implicit time integration described by Tapp and White (1976)) and are damped by the filter with an e-folding time of about 50 time steps. The diffusion is non linear so an accurate calculation of the effect is not possible. Using a typical value for the diffusion coefficient ($10^4\ m^2 s^{-1}$) suggests that the high frequency short wave length sound waves will be damped by diffusion with an e-folding time of about 100 time steps. Thus we may expect differences in the surface pressures to persist. In practice small scale features, eg a trough along the NE coast shear line, adjust within two hours, but substantial differences remain on larger scales after six hours. The important result is that these differences are confined to the surface pressure field itself and do not show themselves in any other way.

5 CONCLUSION

The initial conditions for a local weather forecast, which started at 1200 local time on a good sea breeze day, have been varied and the relative importance of specifying correctly the temperature, wind and surface pressure fields has been assessed. The result is that the forecast is controlled principally by the initial temperature field, and that the wind field adjusts to the temperature field within about an hour. Changes in the initial mesoscale surface pressure field had no effect on the forecast.

Whether these conclusions are valid in a wide range of circumstances must be determined by further experiments of the same sort in other meteorological conditions. They are obviously limited by the fact that the model and forecast were dry, so the consequences of the formation of cloud and rain due to erroneous vertical motion in the initial conditions have not been studied. Nevertheless, it is quite clear that it is important that the initial temperatures are realistic, and this is not surprising since the geostrophic control of small scale ($\sim$ 100 km) weather systems is weak.

The most interesting conclusion is that concerning the initial surface pressure field. It apparently contrasts with the results of Carpenter (1979) who found that a forecast for the same sea breeze day was very sensitive to the movement of the dominant anticyclone. However, even for scales as large as the whole model (600 km), geostrophic adjustment theory suggests that the pressure field will adjust to the wind field, and any residual tendency for the average wind field to adjust to the average pressure field will be minimised by the fact the normal component of the velocity is imposed at the model boundaries. On these scales, information about the synoptic situation can be conveyed through the wind field far more efficiently than through the surface pressure field, and this is how it is done for the model used here. It is only by convention that the synoptic situation is illustrated by an analysis of the pressure, rather than by an analysis of the vertical component of vorticity or the stream functions.

This experiment was idealised in that it supposed full knowledge of all meteorological variables. In practice we have to interpret the observations that are available. Two forecasts were based on initial conditions that supposed qualitative knowledge of the boundary layer structure, which could be inferred from cloud type and height, satellite pictures and current weather observations, and screen level temperatures only. It is encouraging that, in this situation, these forecasts were good. The result, that changes in the surface pressure field have no impact on the subsequent forecast in this case, does not imply that observations of surface pressure have no value, even in situations like 14 June 1973.

It is well known that, in reality, it is possible to draw substantial conclusions from surface pressure observations alone. Rather, this result shows that the information contained in the surface pressure observations must be transferred to the other fields as part of the process of analysing the observations and calculating initial fields. If the initial fields of wind and temperature are not such as would produce the observed surface pressures, then the information content of the surface pressure observations will be lost, at least in sea breeze situations over the UK. It is likely that a great deal of work will have to be done to discover the best use to make of the large quantity of very high quality observations of surface pressure and tendency.

It is not possible to draw firm conclusions at this stage about which observations will prove useful in practice. Clearly, any observations of temperature or stability will be extremely useful. One of the most urgent problems is to discover the best use to make of screen level observations of temperature, but traditional surface based observations of boundary layer type must be considered seriously. Satellite and radar observations could well provide valuable information about boundary layer type and depth. Equipment installed in aircraft using major airports (reference) could provide temperature measurements that will be a very valuable addition to the synoptic radio sonde network. It is probably misleading to draw conclusions about the value of wind observations from this experiment, but the usefulness of surface pressure observations probably depends on our ability to interpret them in novel ways.

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APPENDIX

For the aspect ratios of interest in the text, atmospheric motion is effectively hydrostatic. If we use the hydrostatic approximation, the only waves that will appear in a linearised analysis about the state of no motion are internal gravity waves and a horizontally propagating sound wave. Geostrophic motion appears as a stationary mode. In order to simplify the analysis, the variation with height of density and the speed of sound c^2 are ignored. The equations of motion are linearised about a basic state of no motion, in which the potential temperature $\theta = \theta_0(z)$ depends on height. $\left[\frac{g}{\theta_0}\frac{\partial\theta_0}{\partial z} = N^2 = \text{constant}\right]$ and the Exner function $P = (p/p_r)^{R/c_p} = P_0(z)$ is defined by its surface value $P_0(0) = 1$ and the hydrostatic relation $c_p\theta_0\,\partial P_0/\partial z = -g$. Using the notation of Tapp and White (1976) the perturbation equations are

$$\frac{\partial u}{\partial t} - fv + c_p\theta_0\frac{\partial P'}{\partial x} = 0 \qquad \text{A1}$$

$$\frac{\partial v}{\partial t} + fu + c_p\theta_0\frac{\partial P'}{\partial y} = 0 \qquad \text{A2}$$

$$c_p\theta_0\frac{\partial P'}{\partial z} = g\frac{\theta'}{\theta_0} \qquad \text{A3}$$

$$\frac{\partial\theta'}{\partial t} = -w\frac{\partial\theta_0}{\partial z} \qquad \text{A4}$$

$$\frac{c_p\theta_0}{c^2}\frac{\partial P'}{\partial t} + \frac{\partial u}{\partial x} + \frac{\partial v}{\partial y} + \frac{\partial w}{\partial z} = 0 \qquad \text{A5}$$

If, in order to be consistent with the assumption of constant density and c^2, we ignore the variation of θ_0 with height, except in equation A4, we can find solutions

$$\chi = Re\left(\tilde{\chi}\,e^{i(\omega t - kx - ly - mz)}\right)$$

where χ is u, v, w, θ', or P', to these equations and $\tilde{\chi}$ is complex. The result is

$$\tilde{u} = \frac{k\omega - ilf}{\omega^2 - f^2}\,c_p\theta_0\,\tilde{P}' \qquad \text{A6}$$

$$\tilde{v} = \frac{l\sigma + ikf}{\sigma^2 - f^2} c_p \theta_0 \tilde{P}' \qquad \text{A7}$$

$$\tilde{\theta}' = -im\theta_0 / g c_p \theta_0 \tilde{P}' \qquad \text{A8}$$

$$\tilde{w} = -m\sigma / N^2 c_p \theta_0 \tilde{P}' \qquad \text{A9}$$

where

$$\frac{\sigma}{c^2} = \frac{k^2 + l^2}{\sigma^2 - f^2}\sigma - \frac{m^2}{N^2}\sigma \qquad \text{A10}$$

ie $\sigma = 0$

or $\sigma_{\pm}^2 = f^2 + N^2 \frac{k^2 + l^2}{m^2 + N^2/c^2} \approx f^2 + N^2 \frac{k^2 + l^2}{m^2}$ A11

or $= f^2 + (k^2 + l^2)c^2$

$\sigma = 0$ is the geostrophic mode. For $m \neq 0$, A11 gives the internal gravity wave mode and the approximation $m^2 >> N^2/c^2$ is consistent with ignoring the variation of density with height. For $m = 0$, A11 gives the horizontally propagating sound waves.

Any initial conditions can be resolved into these modes. At first sight it appears that there are five variables and only three modes, but the hydrostatic relation removes one degree of freedom and Richardson's equation

$$\frac{\partial^2 w}{\partial z^2} - \frac{N^2}{c^2} w = -\frac{\partial}{\partial z}\left(\frac{\partial u}{\partial x} + \frac{\partial v}{\partial y}\right) \qquad \text{A12}$$

(obtained by taking $\partial/\partial t$ of equation A3 and $\partial/\partial z$ of equation A5 and eliminating time derivatives) removes a second degree of freedom. If the initial u, v and P' fields are given by $\chi = Re\left(\bar{\chi}\, e^{-i(kx + ly + mz)}\right)$, then the geostrophic part of these fields is given by

$$c_p \theta_0 \tilde{\bar{P}}'_{(\text{geostrophic})} = \frac{f^2/c^2\, c_p \theta_0 \bar{P} + i f (k\bar{v} - l\bar{u})}{f^2/c^2 + (k^2 + l^2)} \qquad \text{A13}$$

for $m = 0$

$$c_p \theta_0 \tilde{\bar{P}}'_{(\text{geostrophic})} \approx \frac{m^2 f^2 c_p \theta_0 \bar{P}' + i f (k\bar{v} - l\bar{u}) N^2}{m^2 f^2 + (k^2 + l^2) N^2}$$

Finally it is supposed that after adjustment has taken place only the geostrophic mode remains. Thus, for $m \neq 0$, the wind field determines the adjusted state for $f^2 m^2 / \{ N^2 (k^2 + l^2) \} \ll 1$. In the present study $(k^2 + l^2) \sim 10^{-8}$, $m^2 \sim 10^{-5}$, $N^2 \approx 2 \times 10^{-4}\ s^{-1}$ (except within the well mixed layer over land) so $f^2 m^2 / \{ N^2 (k^2 + l^2) \} \sim 10^{-1}$ and the mass field is expected to adjust to the wind field. However, this is not an appropriate application of the theory, as discussed in the text. For $m = 0$, the wind field determines the adjusted state for $f^2 / \{ (k^2 + l^2) c^2 \} \ll 1$. In the present study, this variable is 10^{-5}, and in fact A13 gives

$$\tilde{\bar{P}}'_{(\text{geostrophic})} \sim 10^{-5} \bar{P}'$$

. Since a change in surface pressure affects only the $m = 0$ components (through the hydrostatic relation), we expect it to be manifested only in sound waves, as discussed in the text.

TABLE CAPTIONS

Table 1

Source of the various fields in the seven sets of initial conditions. All the fields are valid at 1200 GMT. The calculation of the pressures, and of the temperatures when "mesoscale at 50 m" is specified, is described in the text. The labels SS etc attached to four sets show the origin (S = synoptic, M = mesoscale) of the winds and temperatures.

Table 2

The effect of changes (i) (winds), (ii) (temperatures) and (ii)(a) (modified temperatures) in the eight areas A to H identified in the text. A blank entry indicates that there was no effect.

TABLE 1

	Forecast	Initial winds	Initial temperatures	Initial surface pressure
1	MM	Mesoscale	Mesoscale	Mesoscale
2	SM	Large scale	Mesoscale	Mesoscale
3	MS	Mesoscale	Large scale	Large scale
4	SS	Large scale	Large scale	Large scale
5		Mesoscale	Mesoscale at 50 m	Mesoscale
6		Large scale	Mesoscale at 50 m	Mesoscale
7		Large scale	Mesoscale at 50 m	Large scale

TABLE 2

	(i)		(ii)		(ii)(a)	
	2 hrs	6 hrs	2 hrs	6 hrs	2 hrs	6 hrs
A	Stronger SW flow	Shear line to E moved N	The whole forecast is completely different (underdeveloped)		Flow veered	
B	Shear line further N	20 km further N		10 km behind		Shear line further N
C	Shear line further N	Further N		10 km further N		
D	Slack winds become southerly	Shear line further N		N Devon sea-breeze under-developed		
E	Coastal winds backed	V slight backing		Winds backed to S of shear line		V slight backing
F	No visible difference	10 km further N		30 km behind ie further S	5 km further N	10 km further N
G	All fronts 5 km further N	10 km further N		20 km behind ie less penetration	More penetration in fronts	More penetration
H	Shear line less developed. 10 km to sea.	10 km out to sea		10 km out to sea	10 km further inland	10 km further inland

FIGURE CAPTIONS

Figure 1. The initial potential temperatures on a NS vertical section: (a) the synoptic scale data; (b) the mesoscale data (c) the result of inserting a mixed layer of uniform potential temperature (given by the mesoscale data) into the synoptic scale data. The figures on the vertical axis are height, in metres, for each of the model levels.

Figure 2. Initial winds on an NS vertical section. The components parallel to the section are shown, and the magnitude is indicated by the length of the arrows: (a) synoptic scale data; (b) mesoscale data. Every other grid point is shown except at the northern boundary, where two rows are omitted.

Figure 3. The initial sea level pressure fields: (a) synoptic scale data; (b) mesoscale data.

Figure 4. 2 hour forecasts of 50 m winds, valid at 1400 GMT: (a) forecast SM (synoptic scale winds, mesoscale temperatures); (b) forecast MM (mesoscale winds and temperatures); (c) forecast MS (mesoscale winds, synoptic scale temperatures). The strength of the wind is proportional to the length of the arrow, and every other grid point is shown.

Figure 5. 6 hour forecasts of 50 m winds, valid at 1800 GMT: (a) forecast SM; (b) forecast MM; (c) forecast MS.

Figure 6. 2 hour forecasts of vertical velocity at 225 m, valid at 1400 GMT: (a) forecast SM; (b) forecast MM; (c) forecast MS.

POTENTIAL TEMPERATURE ISOTHERM INTERVAL : 1 DEG C

FIG. 1 (a)

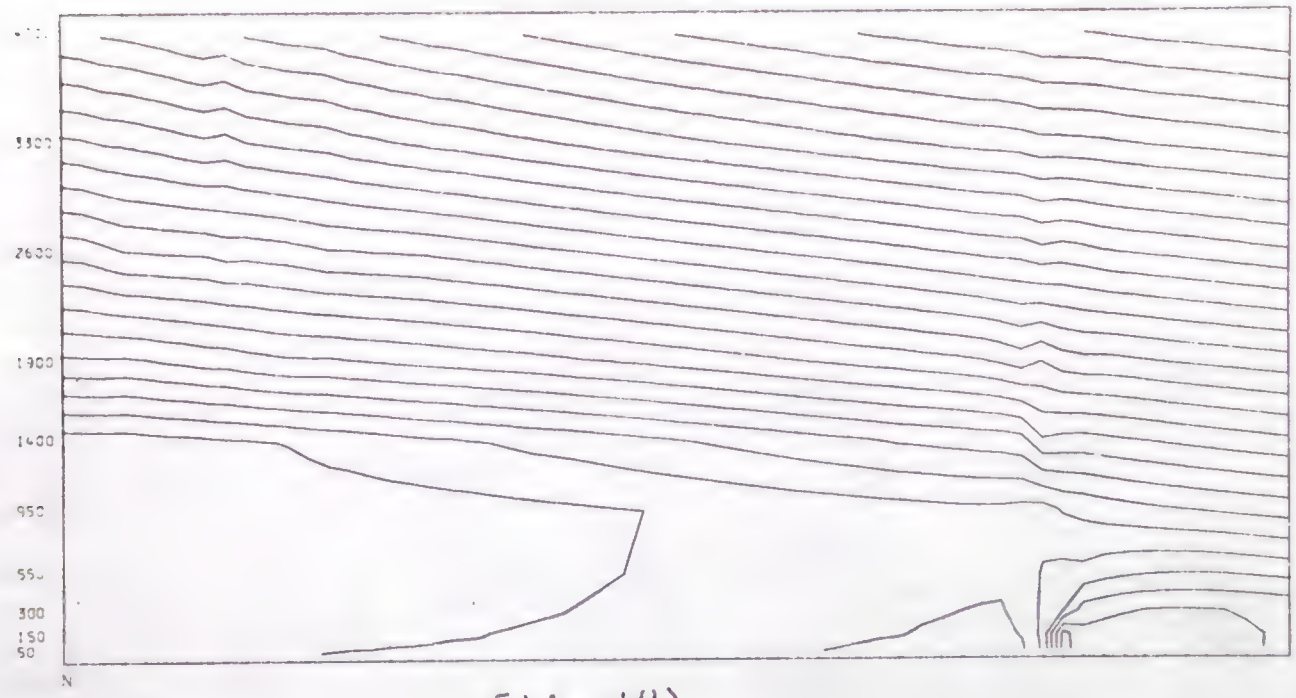


FIG. 1(b)

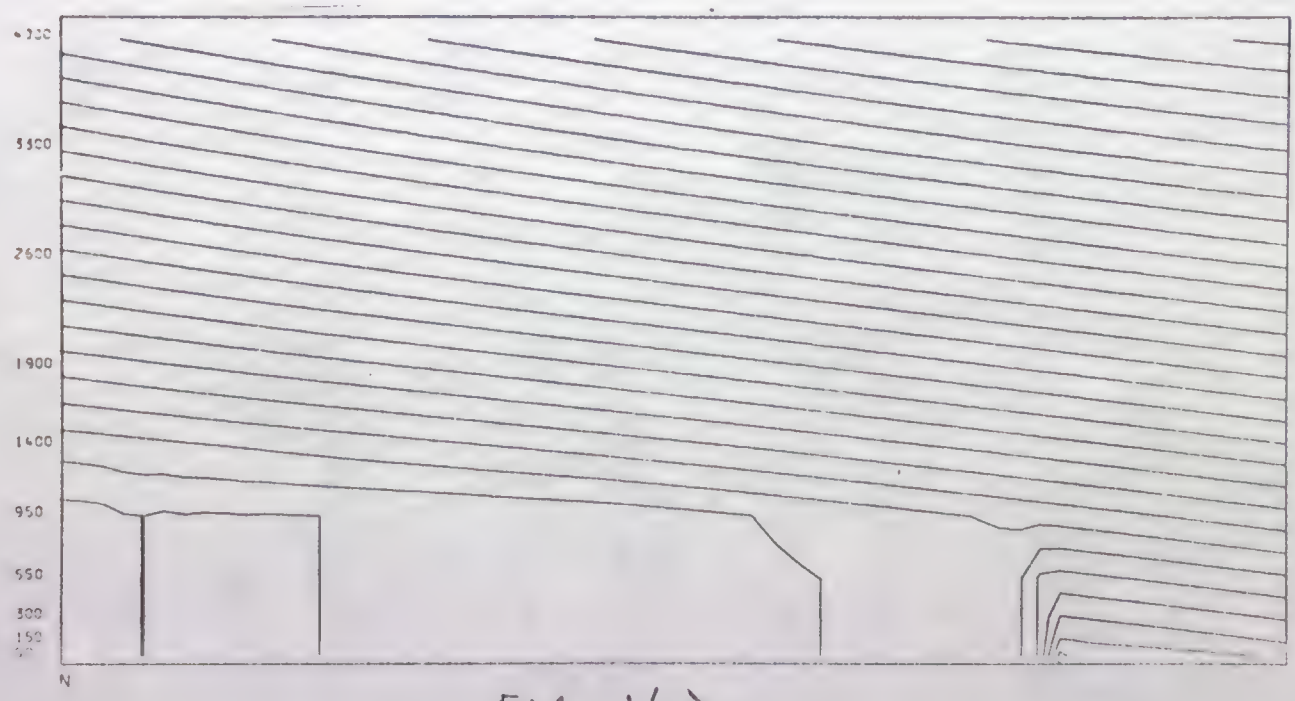


FIG. 1(c)

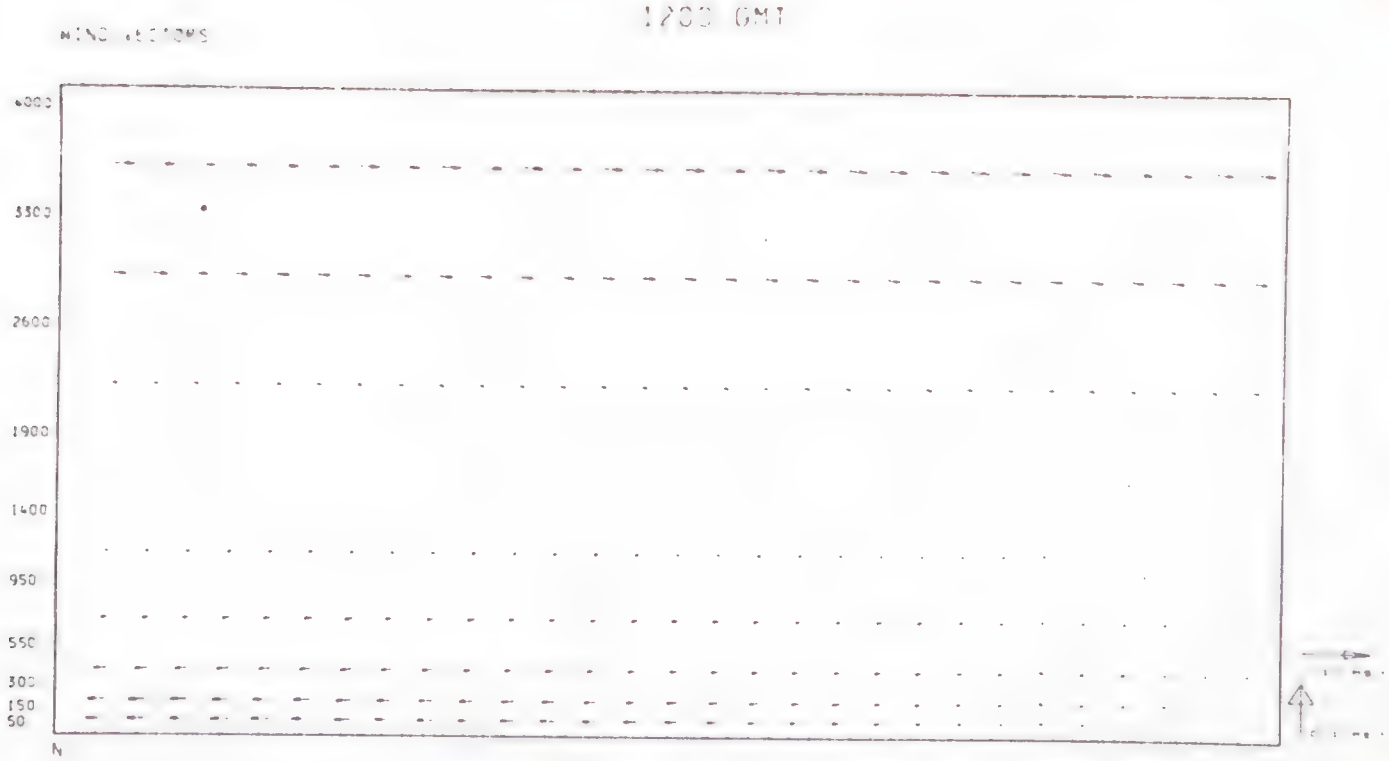
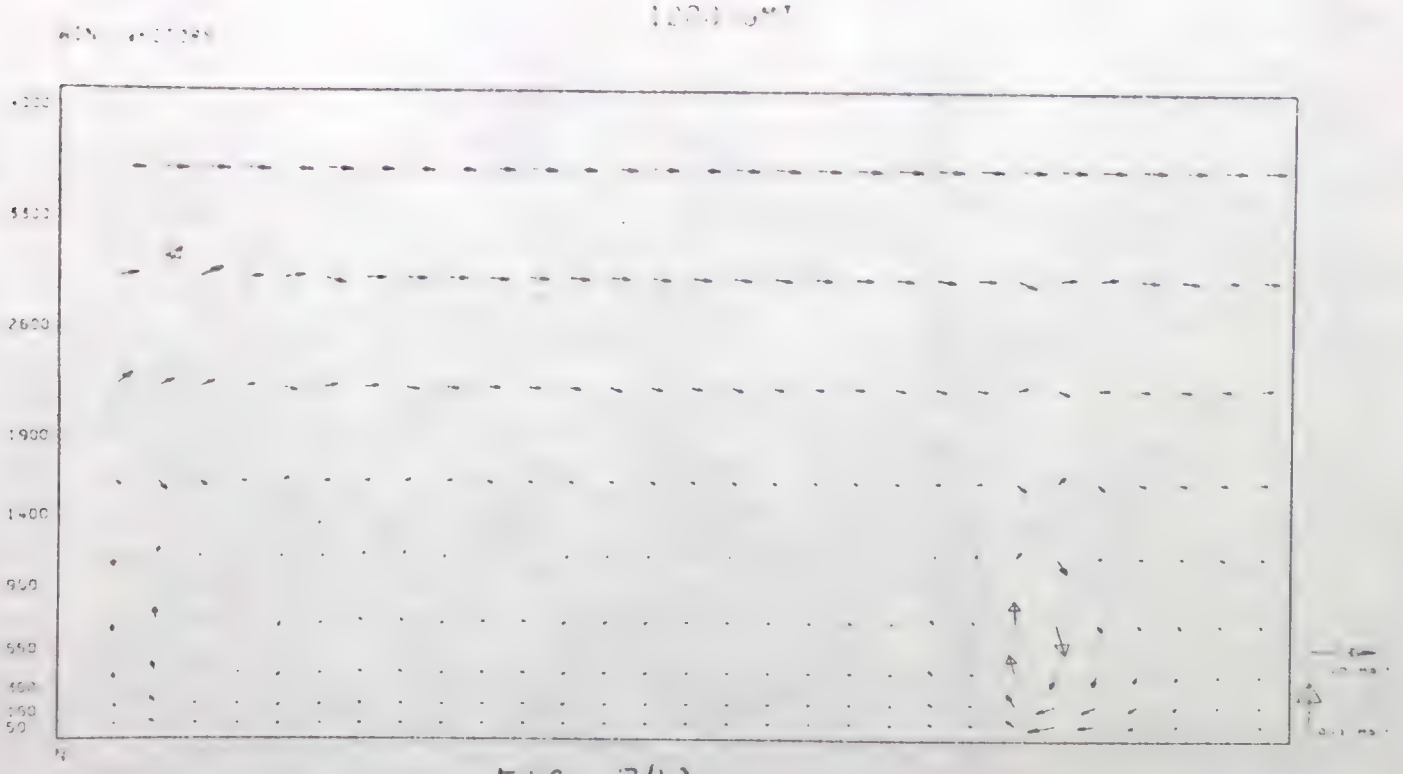

4000
3500
2600
1900
1400
950
550
300
150
50
N

FIG. 2(a)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2600
1900
1400
950
550
50
N

FIG. 2(b)

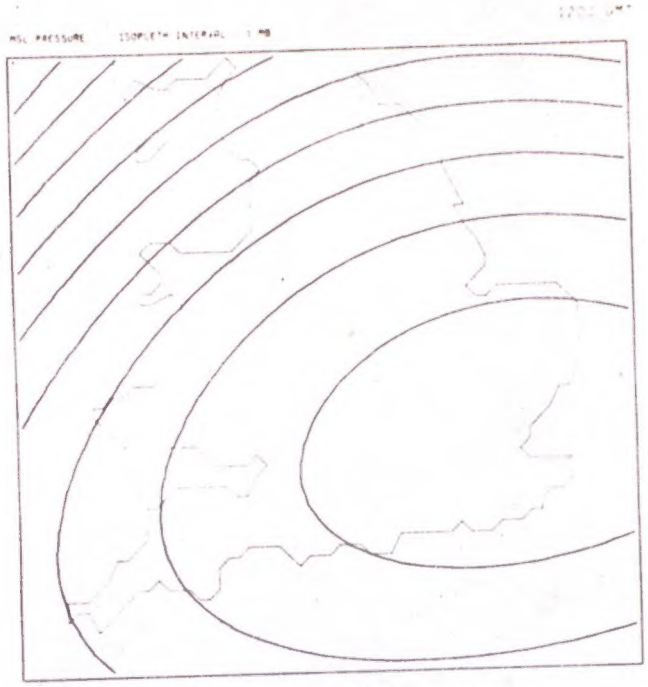

FIG. 3(a)

FIG. 3(b)

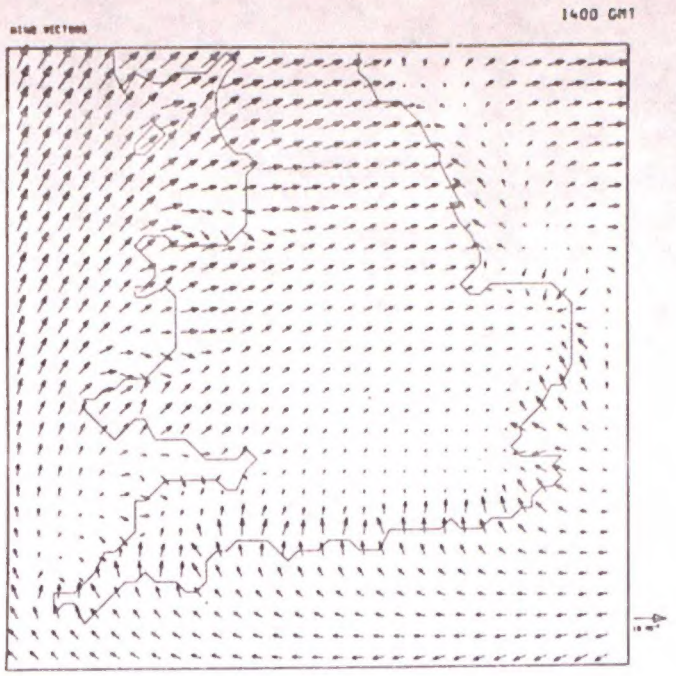

FIG. 4(a)

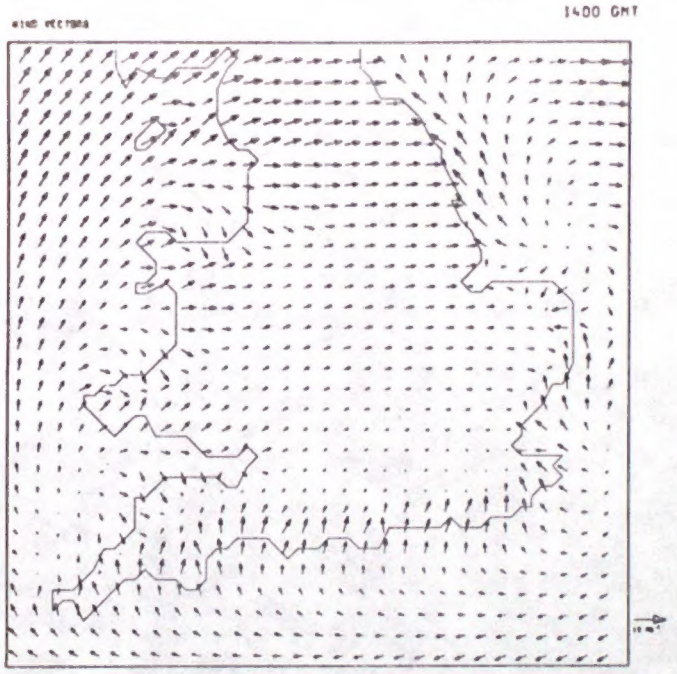

FIG. 4(b)

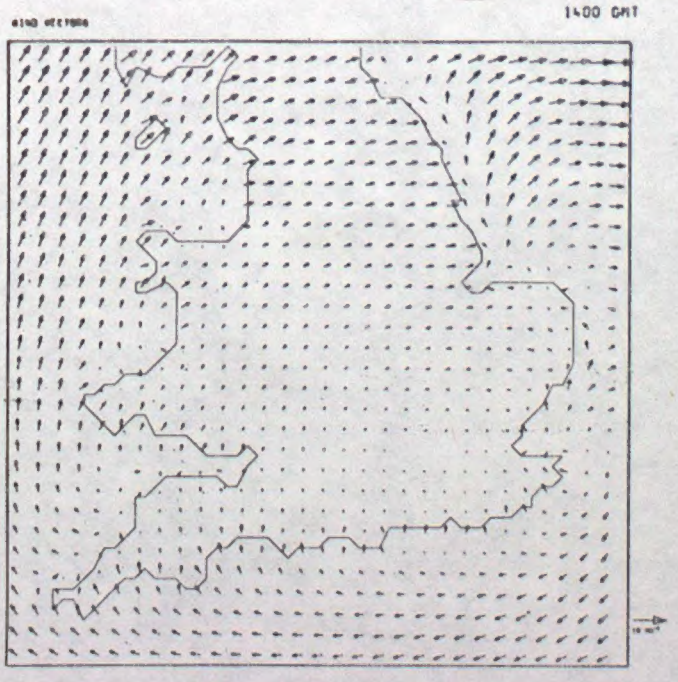

FIG 4(c)

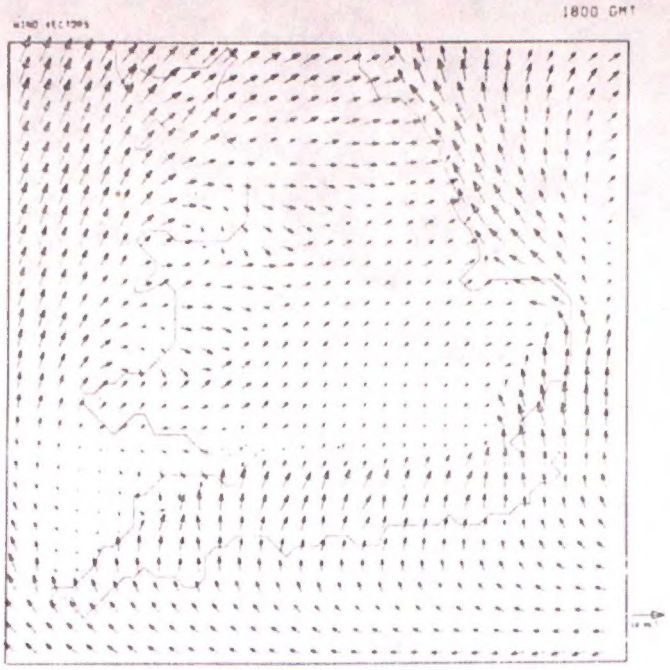

FIG 5(a)

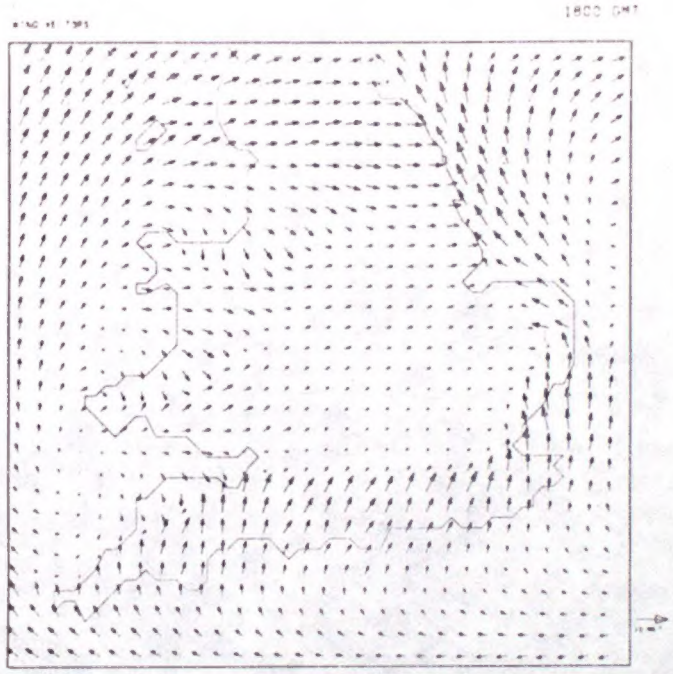

FIG. 5(b)

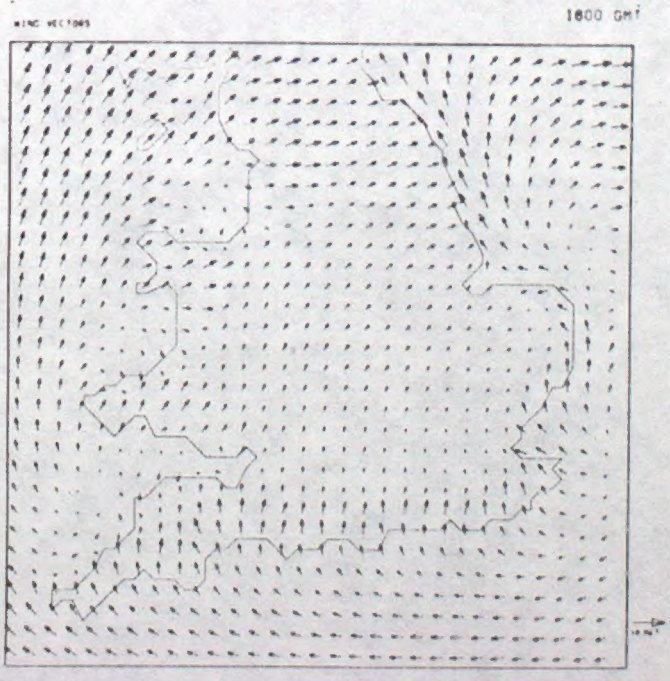

FIG. 5(c)

FIG. 6(a)

FIG. 6(b)

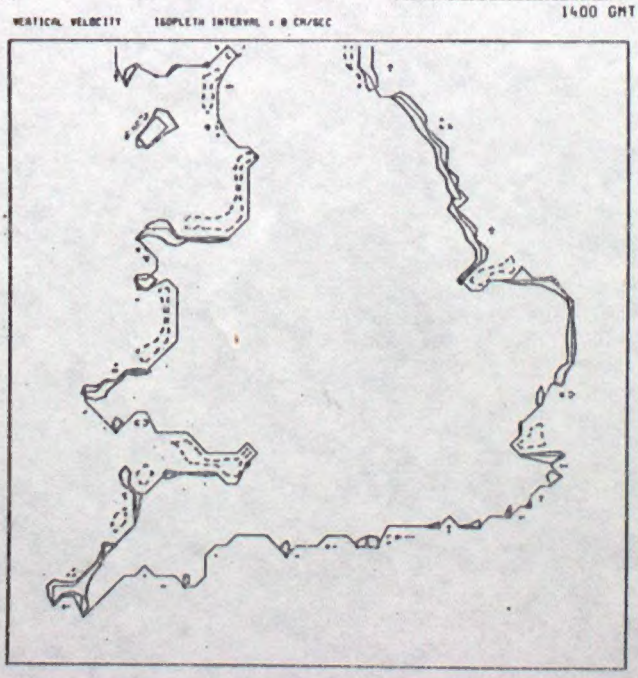

FIG 6(c)